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False positives and shallow eclipsing binaries in transiting exoplanet surveys

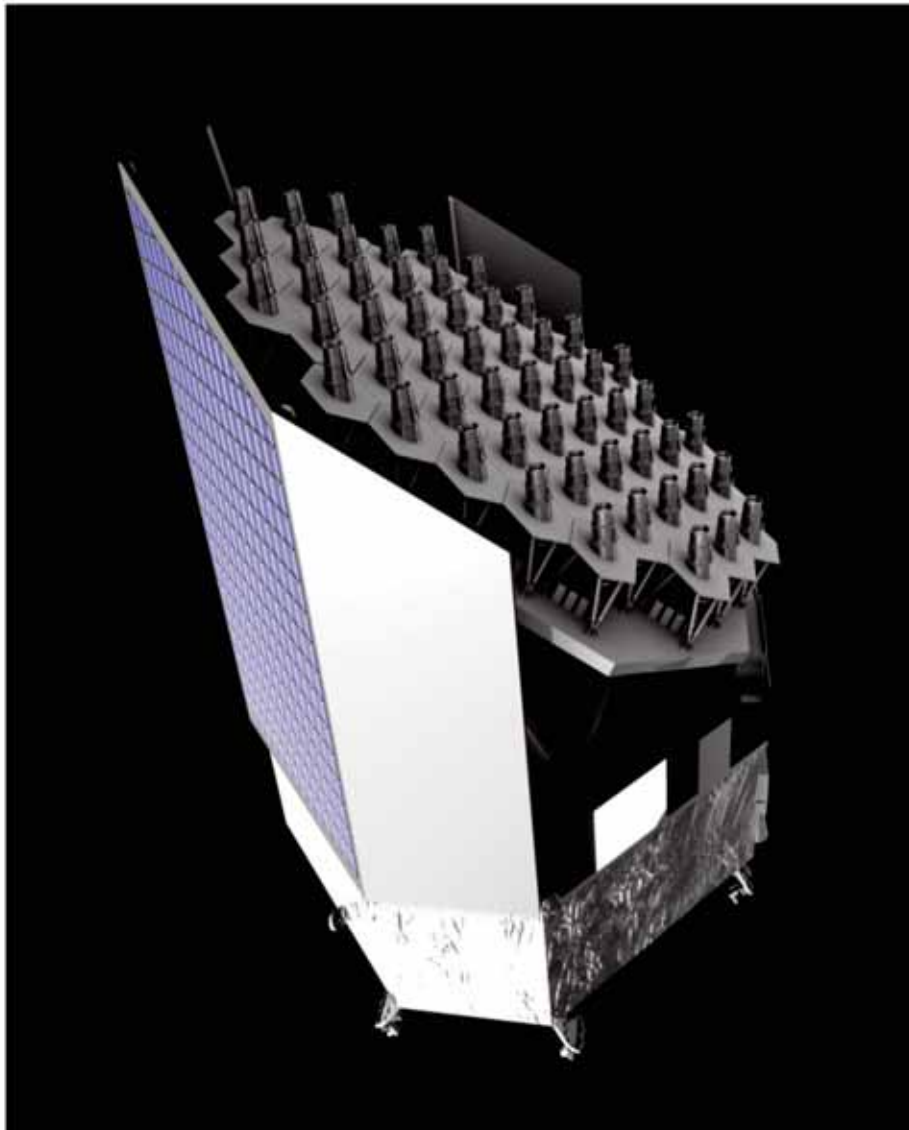
.....

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OUTLINE

False Positives in Transiting Exoplanet Surveys



- Galaxy simulation
- Binary analysis
- Exoplanet distribution
- Results

Image credit: Thales Alenia Space
Image shows Thales Alenia Space concept,
18 February 2010, from assessment phase

METHODOLOGY

KIWI: *Kepler Information With Interest ...*

- Take the Kepler observed output in both the eclipsing binary and the confirmed exoplanet populations
- Apply to a synthetic Galaxy
- Simulate an eclipsing binary and an exoplanet population
- Interpret using PLATO precision

Image credit: NASA JPL



Binary Stellar Evolution Population Synthesis

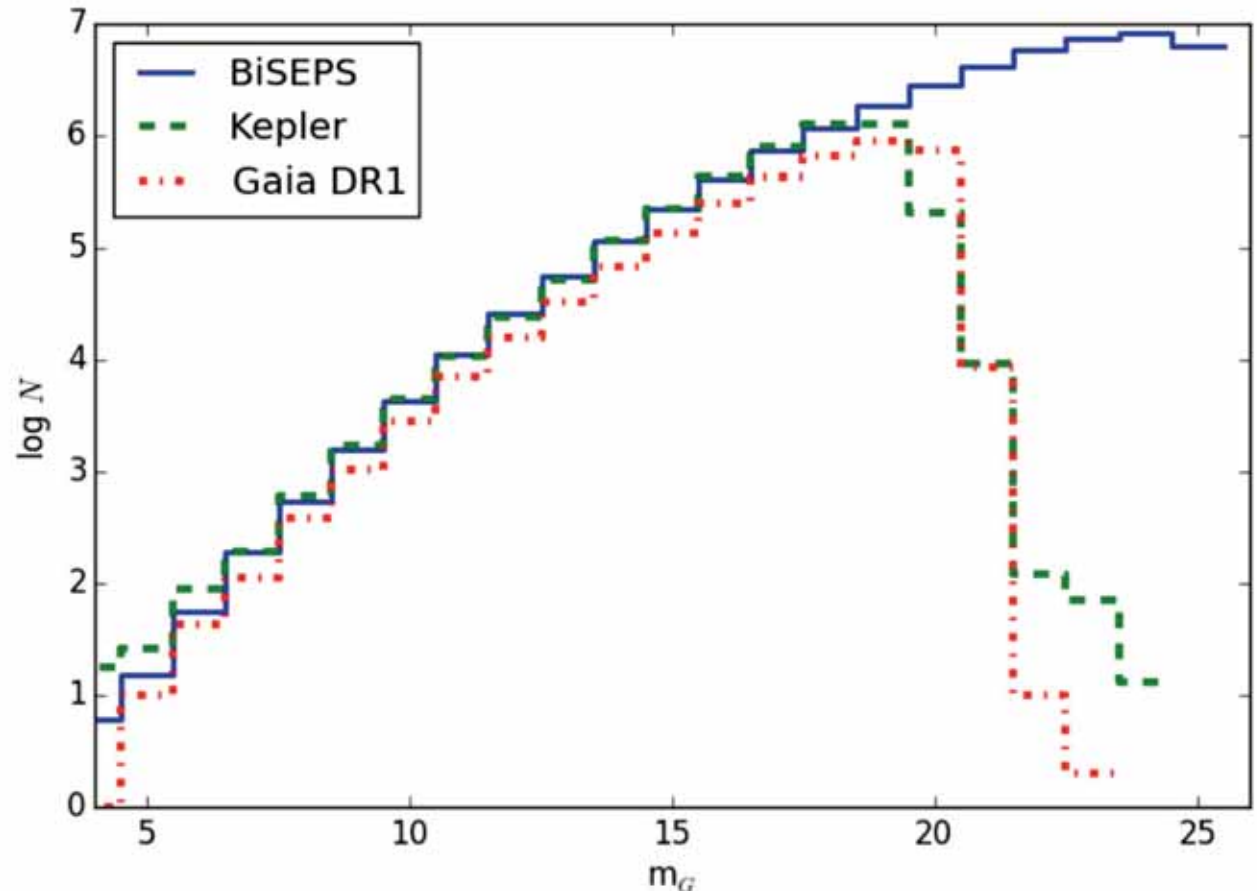
- Based on stellar evolution fitting formulae of Hurley et al (2000) and binary evolution fitting formulae of Hurley et al (2002)
- Creates a synthetic population of both binary systems and single stars by evolving the stars self-consistently from formation
- These models are then seeded into a model of the Galaxy, which uses the fully evolved models as well as information on extinction

Galaxy model:

- Two-disc model (thin and thick) with each disc described by a double exponential
- Star formation is constant from 13-10 Gyr ago in the thick disc ($Z = 0.0033$)
- Star formation is constant over the past 10 Gyr in the thin disc ($Z = 0.02$)
- Kroupa initial mass function

Synthetic Kepler and PLATO fields

- A synthetic Kepler field had previously been generated and calibrated (Farmer, Kolb & Norton, 2013)
- PLATO simulations focus on the proposed Long Look fields in Rauer et al (2014)
- PLATO field calibration verified against the current Kepler Input Catalogue hosted on MAST and Gaia DR1 (illustrated)



KEPLER OBSERVATIONS



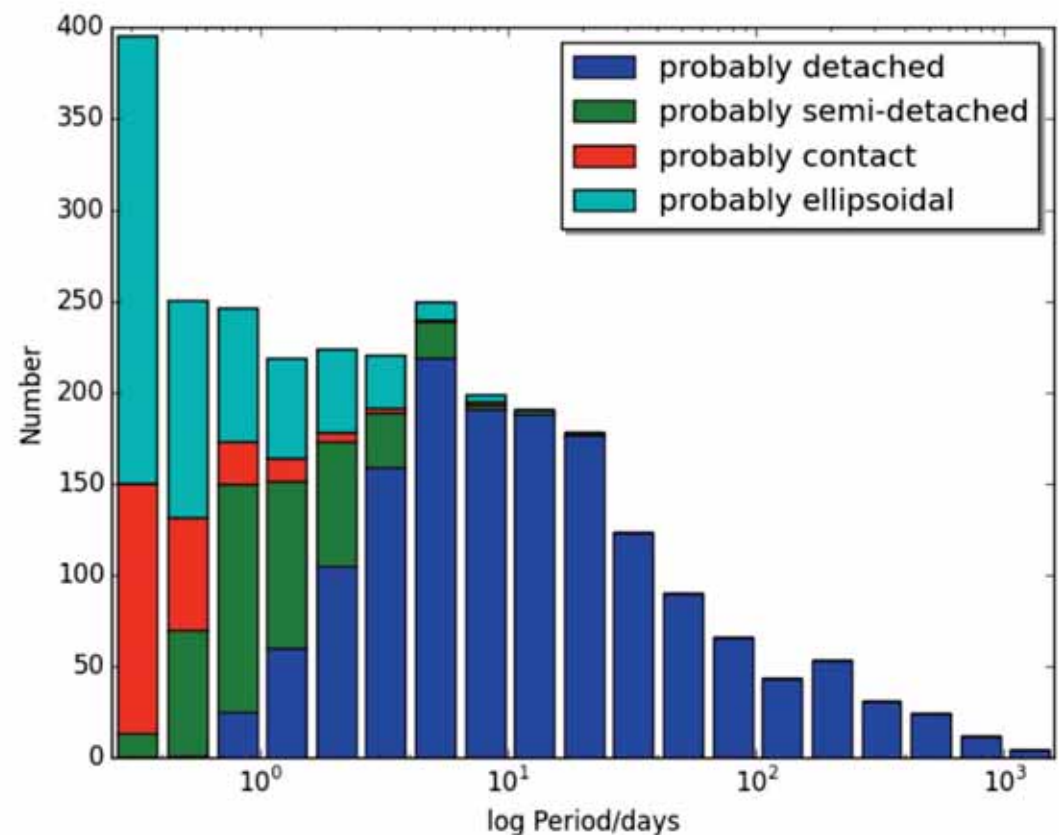
NASA Exoplanet Archive (NExSci):

- Potential eclipsing binaries are identified by a “Significant Secondary” flag
- May be blended or unblended

Kepler Eclipsing Binary Catalogue:

- Unblended confirmed eclipsing binaries

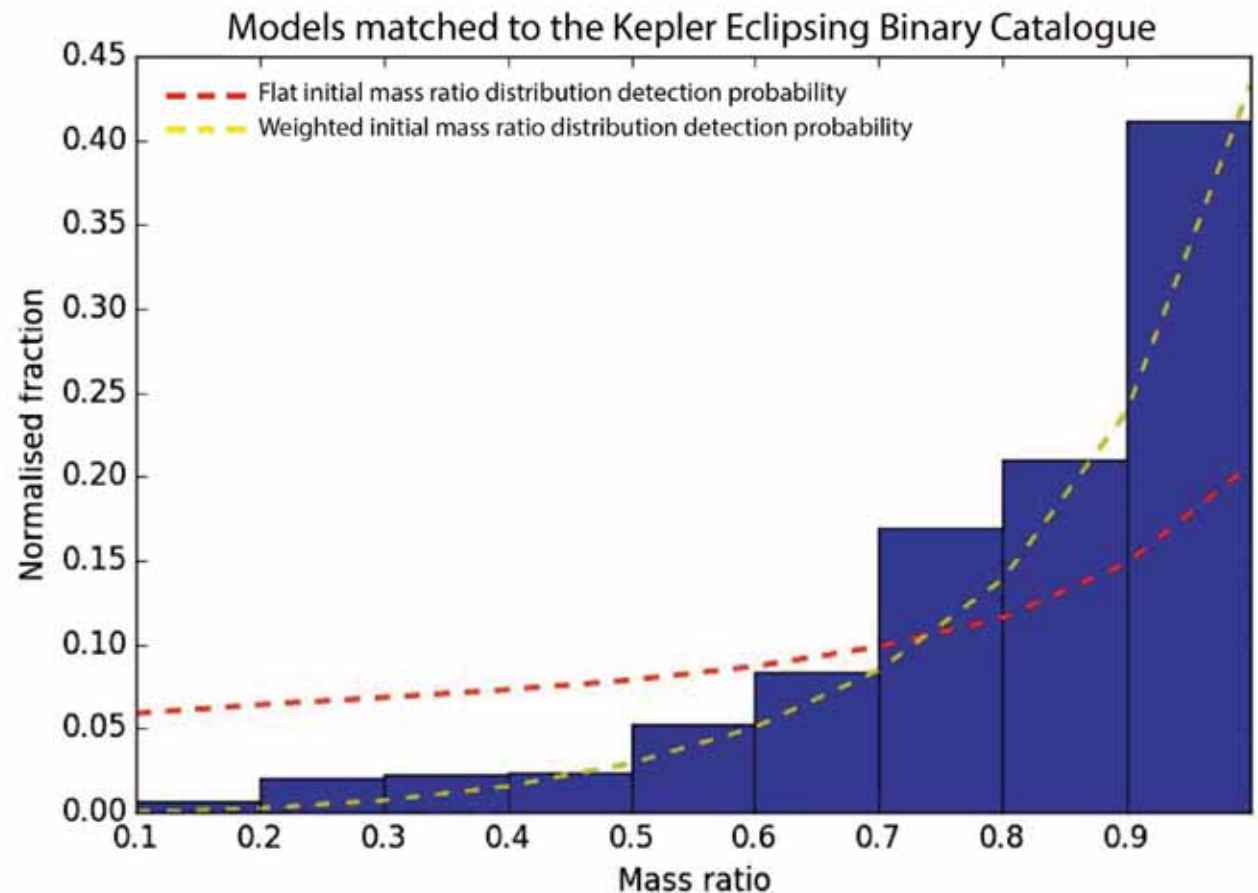
The likely distribution of unblended eclipsing binaries by binary type from the morphology parameter in the Kepler Eclipsing Binary Catalogue. Interpretation of the parameter is from Matijević et al (2012).



CALIBRATION

Eclipsing Binaries

- $P < 10$ days: use Kepler Eclipsing Binary Catalogue to calibrate the initial mass ratio
- Sample size: 971 systems
- Our simulations assume $e = 0$: binaries with $P < 10$ days are likely to have circularised

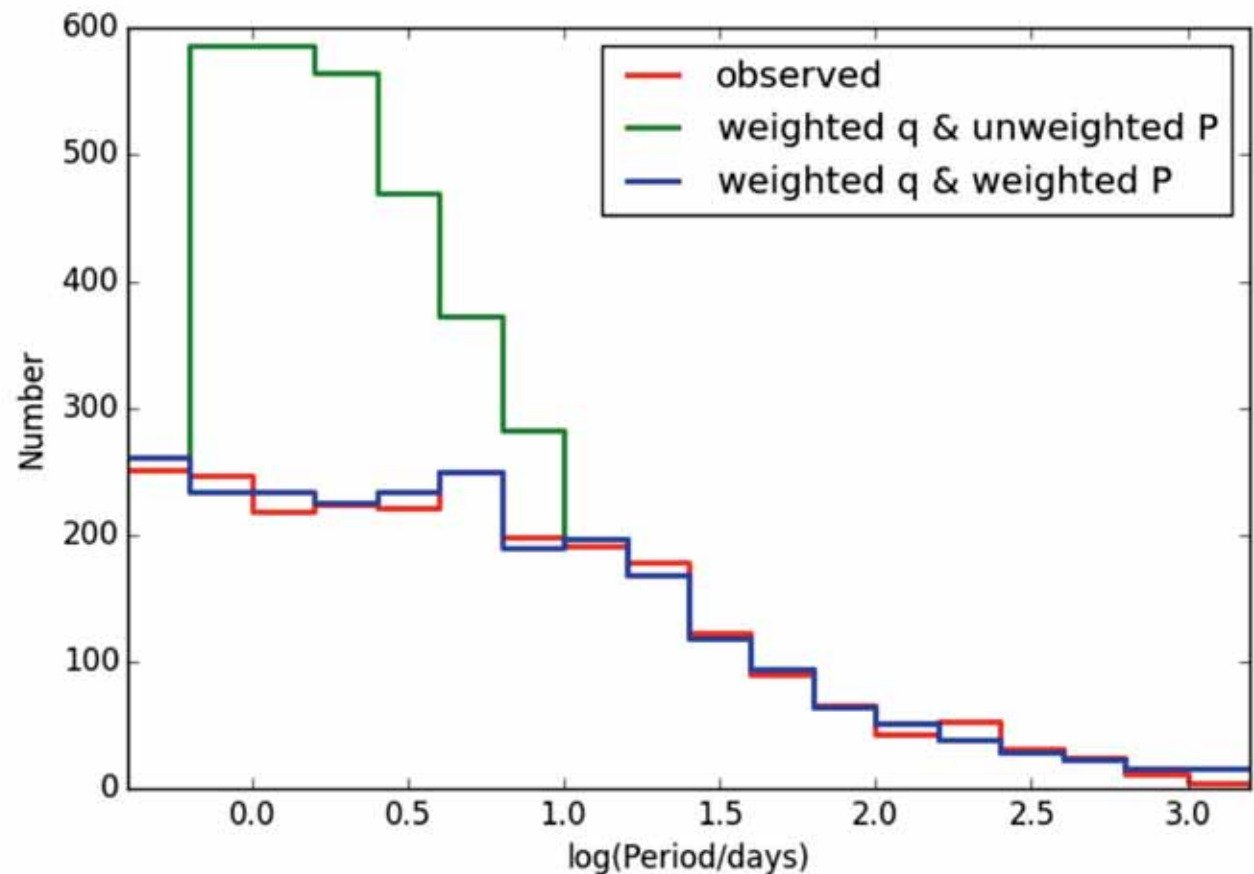


CALIBRATION

Eclipsing Binaries

- All systems: use Kepler Eclipsing Binary Catalogue to further calibrate by orbital period

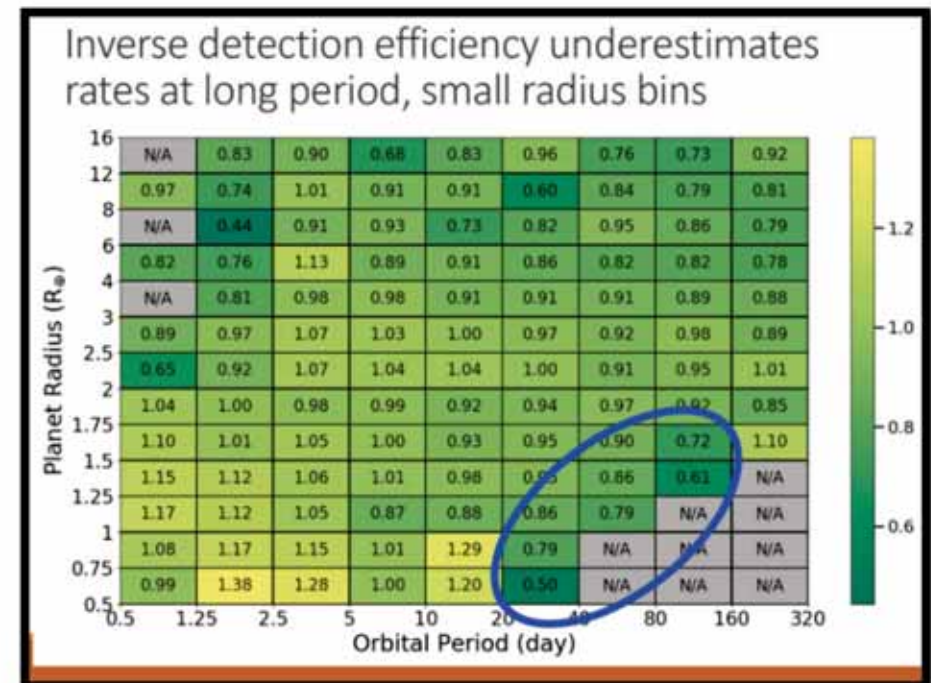
- $P < 10$ days: calibrate by initial period distribution and initial mass ratio
- P 10 to ≈ 64 days: calibrate by initial mass ratio, initial period distribution is flat
- $P > \approx 64$ days: both initial mass ratio and initial period distribution are flat



CALIBRATION

Intrinsic Exoplanet Distribution

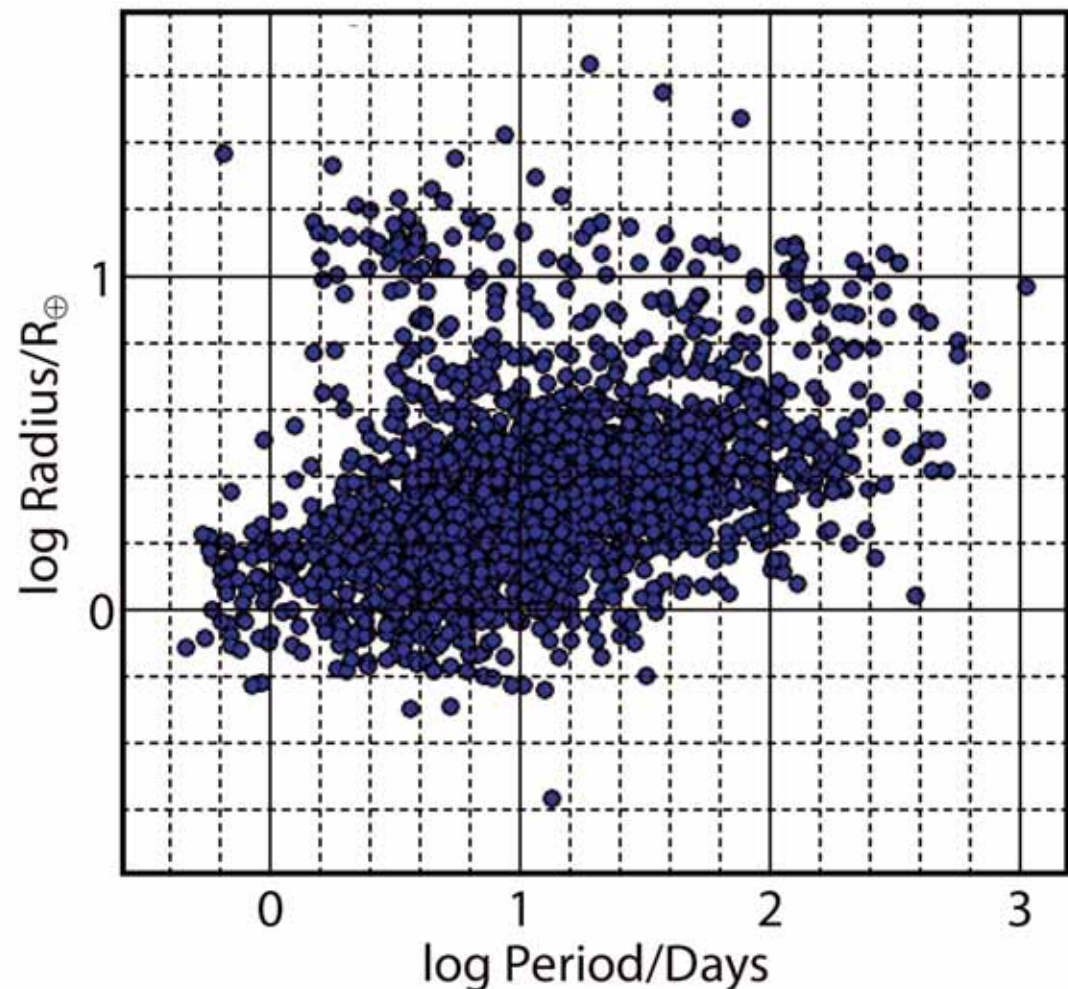
- Our method: applying an Inverse Detection Efficiency Method (IDEM) to Kepler observations, DR25, using a synthetic galaxy modelled by BiSEPS
- IDEM uses the geometric transit probability to assess the likelihood of observing a given planet around a given star
- An alternative method is approximate Bayesian computation (ABC) demonstrated by Danley Hsu at the Kepler & K2 Science Conference, June 2017: his results (right) indicate general agreement between the two types of method except in the small radius/long period regime



CALIBRATION

Intrinsic Exoplanet Distribution

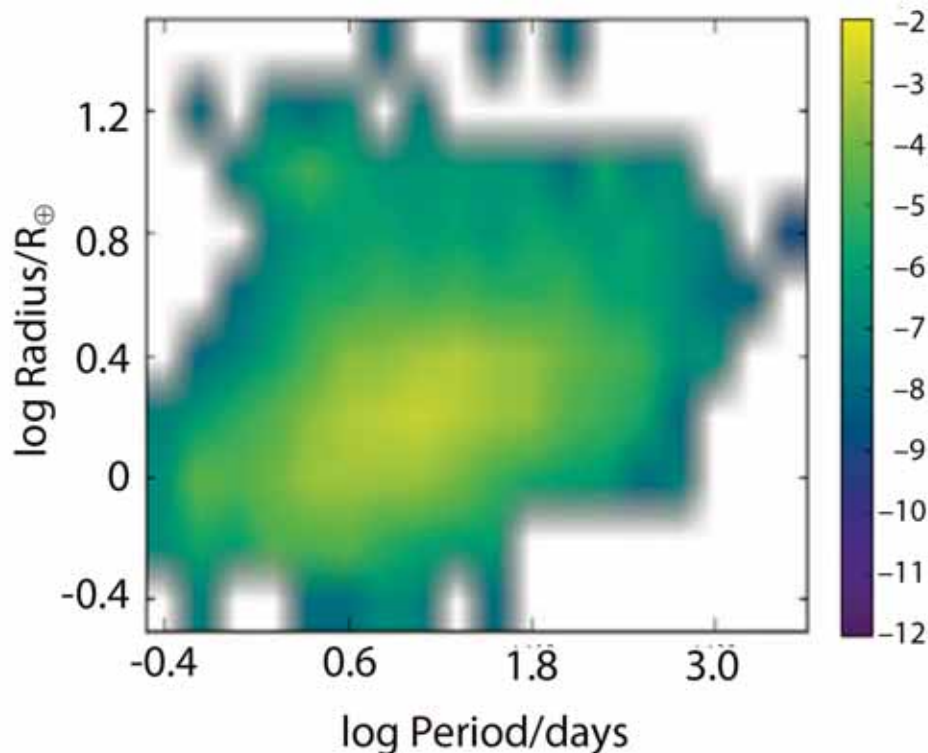
- Confirmed planets, Kepler DR25, by radius and period
- DR25 uses updated stellar parameters, so planet radii are more accurate
- Note
 - sub-Jovian desert
 - dependence of giant planet maximum radius on orbital distance



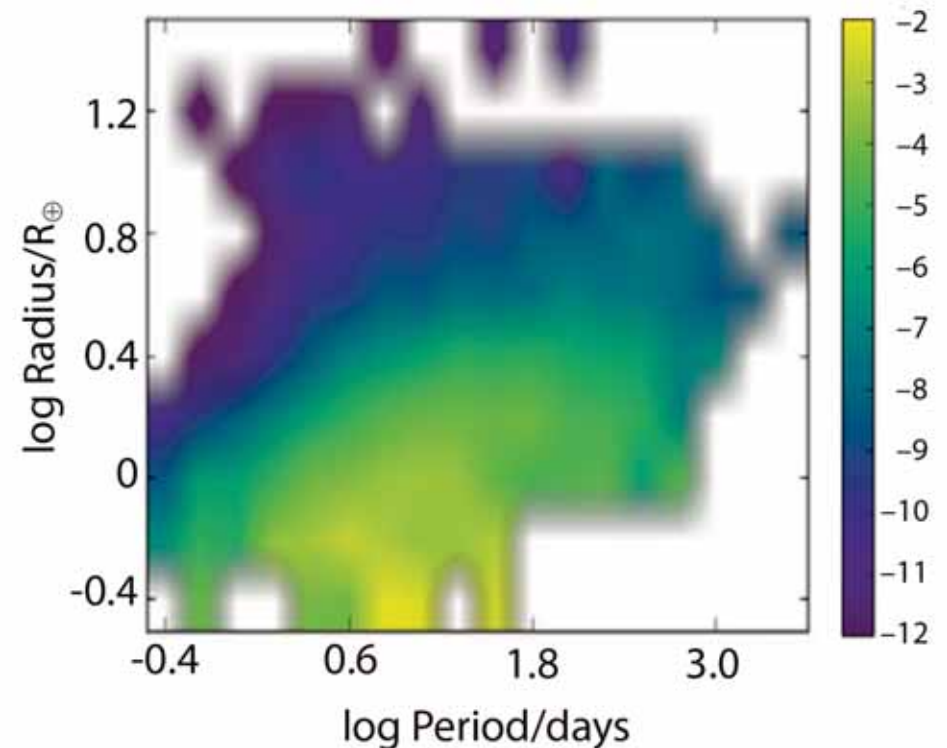
CALIBRATION

Intrinsic Exoplanet Distribution

Normalised observed distribution,
Kepler DR25,
non-zero bins only



Our normalised intrinsic
distribution, non-zero bins in
Kepler DR25 only (right)



RESULTS

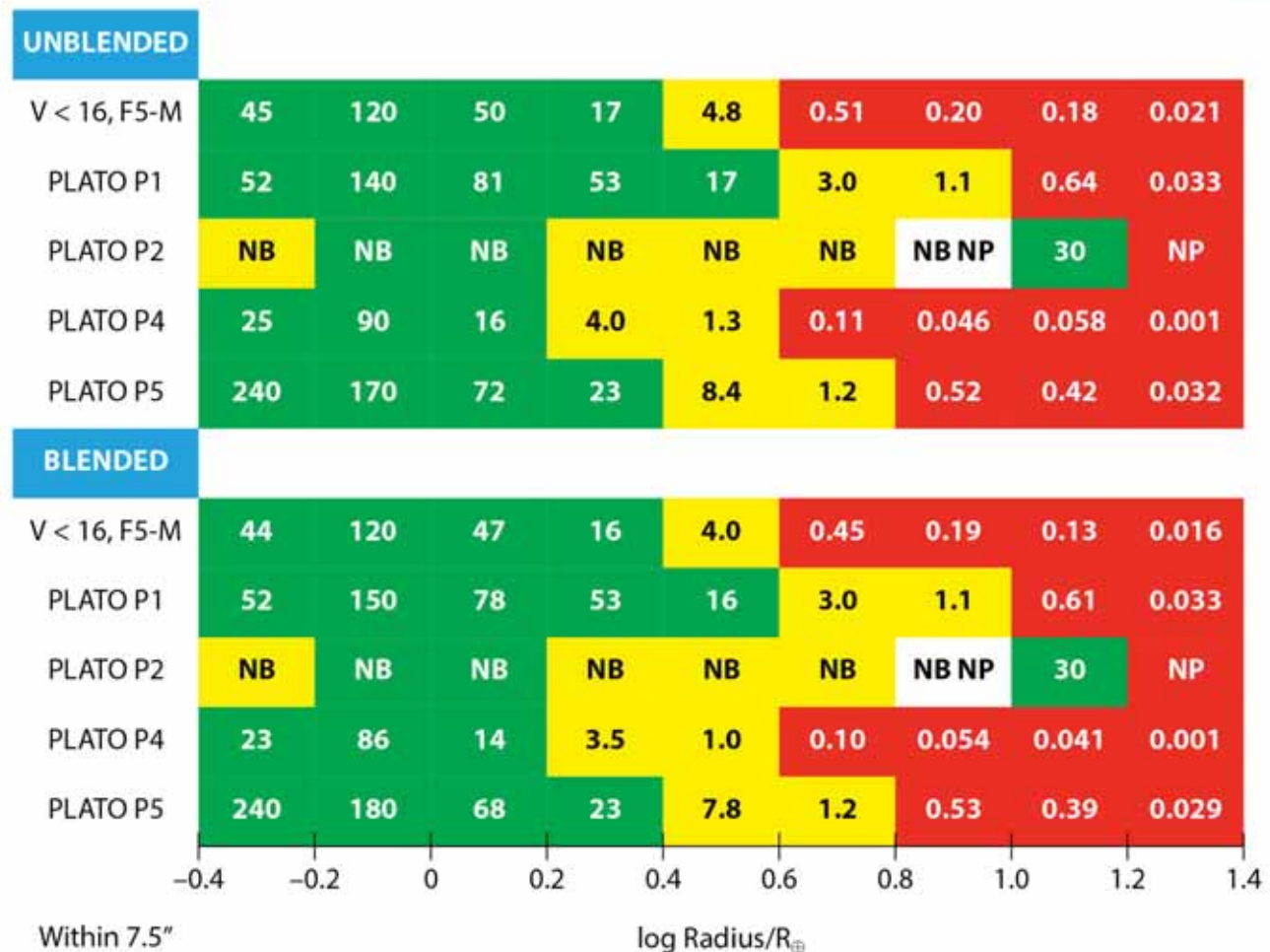
Ratio planets:binaries, LLN, same pixel

Full field, $< 7.5''$

- **Green:** More than 10 planets for each binary, so don't worry!
- **Yellow:** 10 or fewer planets for each binary, so be careful ...
- **Red:** More binaries than planets, be extremely careful!

Error is square root of N

NB: no binaries; NP: no planets



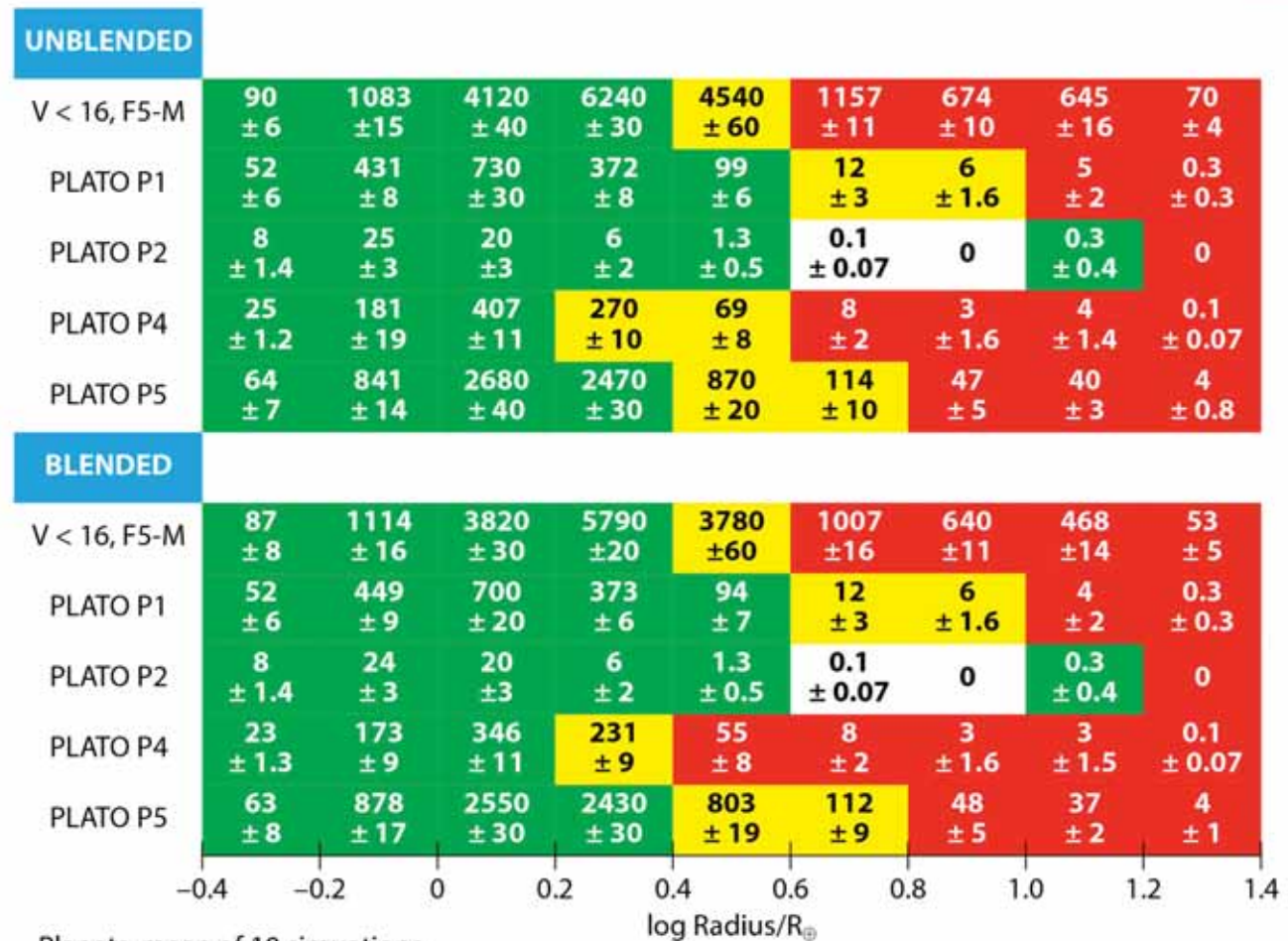
RESULTS

Planets, LLN, full field

Mean of 10 simulations

Error is square root of N

Colours matched to bins in previous slide



Planets, mean of 10 simulations

RESULTS

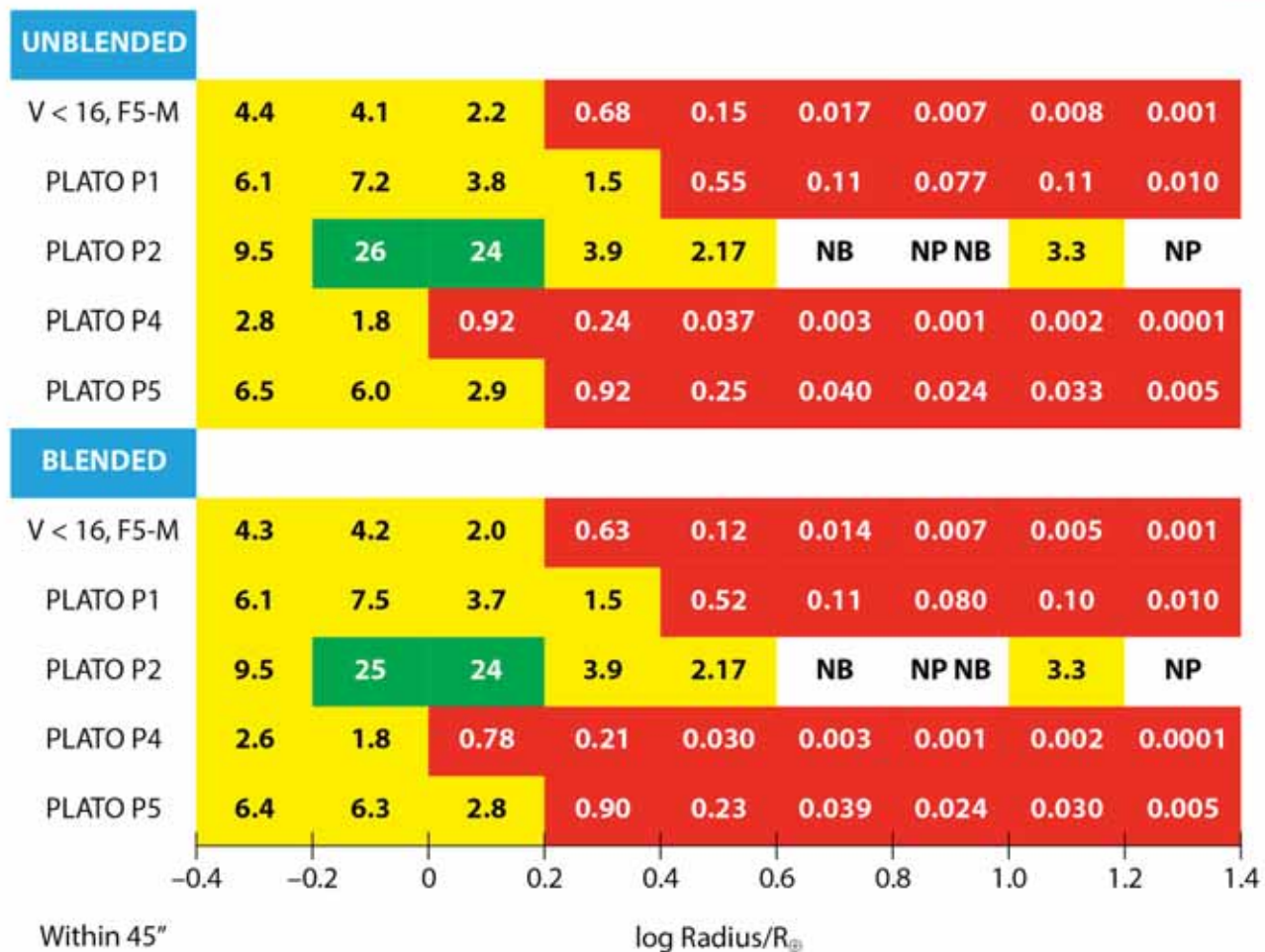
Ratio planets:binaries, LLN, same imagedette

Full field, $< 45''$

- **Green:** More than 10 planets for each binary, so don't worry!
- **Yellow:** 10 or fewer planets for each binary, so be careful ...
- **Red:** More binaries than planets, be extremely careful!

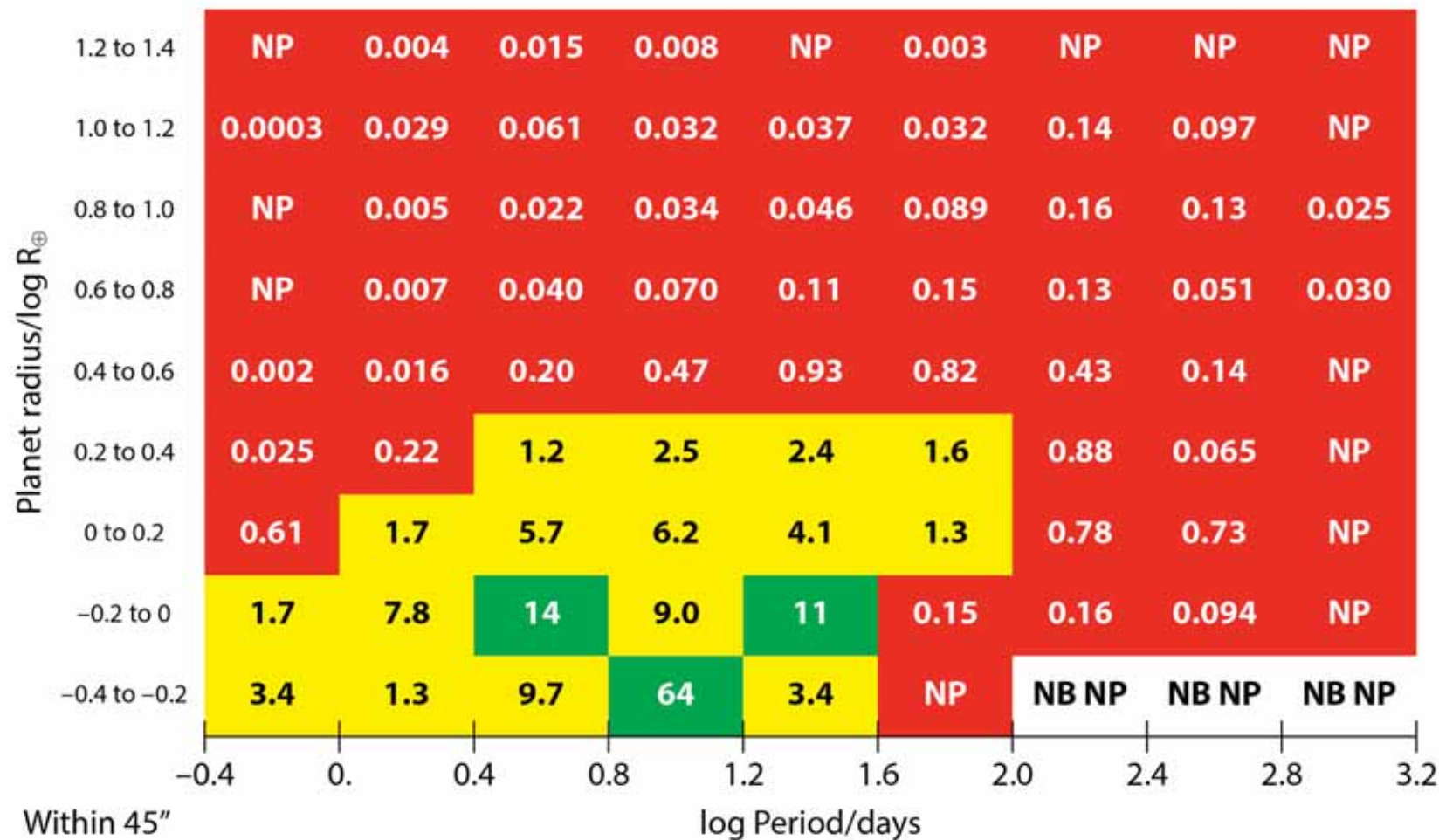
Error is square root of N

NB: no binaries; NP: no planets



RESULTS

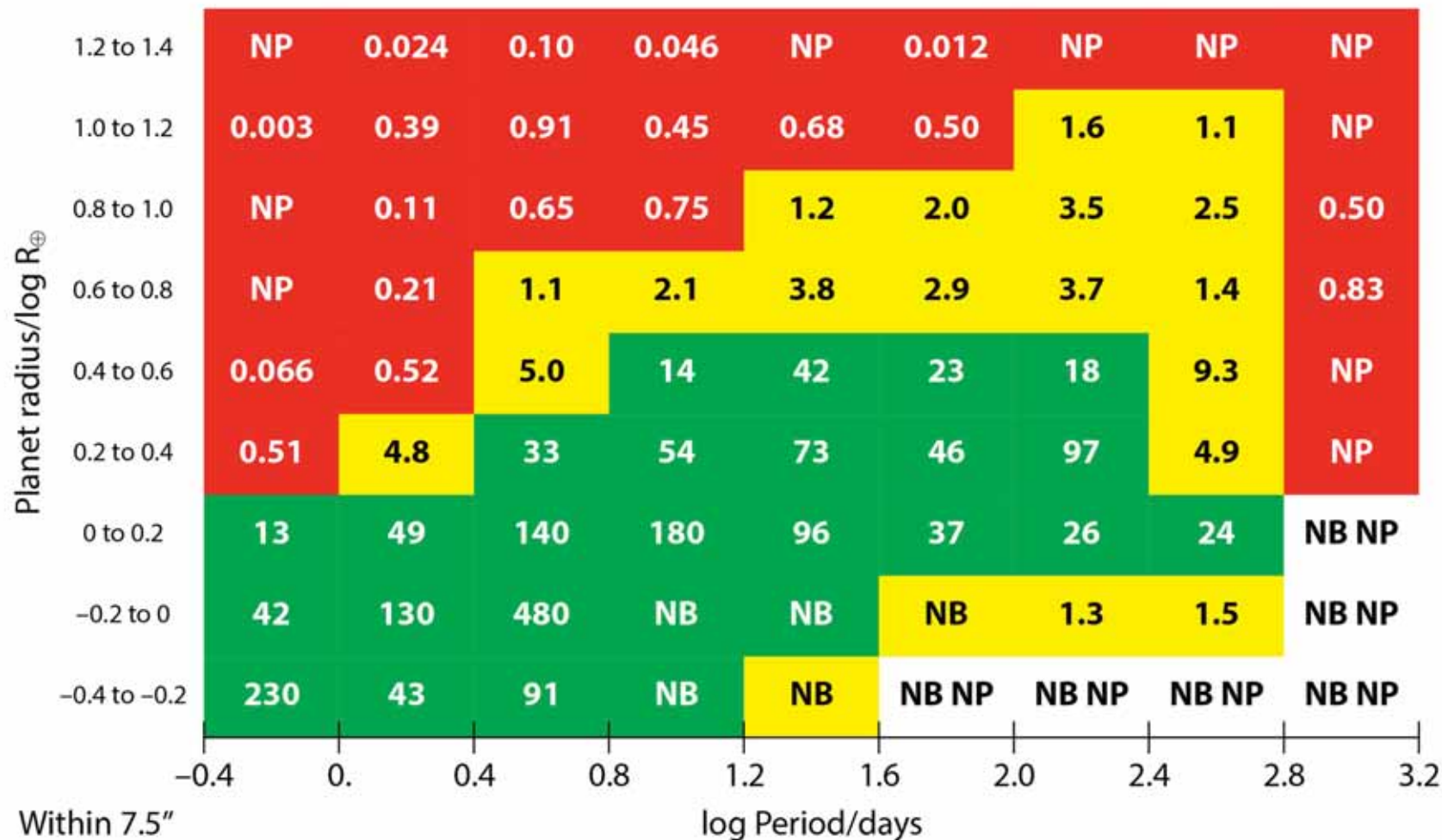
Ratio planets:binaries, P5, same imagedette



NB: No binaries; NP: No Planets; NB NP: neither planets nor binaries

RESULTS

Ratio planets:binaries, P5, same pixel



NB: No binaries; NP: No Planets; NB NP: neither planets nor binaries

RESULTS

Proportion in central region: planets

- Region covered by 4 cameras will give the best resolution, especially in achieving 34 ppm in P1 and 80 ppm in P5
- In P5, 1665 of the 6949 planets in the full field (24%) are in the region covered by 4 cameras in our simulation

Planet Class	LLN					LLS				
	Centre	σ	Full field	σ	Ratio	Centre	σ	Full field	σ	Ratio
Mars	22	4	63	8	35%	30	5	71	7	42%
Earth 1	289	17	878	17	33%	330	4	972	19	34%
Earth 2	672	11	2551	34	26%	741	22	2960	31	25%
Small Neptune 1	512	17	2427	26	21%	555	21	2801	43	20%
Small Neptune 2	134	7	803	19	17%	143	8	897	10	16%
Large Neptune	16	1.7	112	9	14%	20	5	127	4	16%
Giant Planet 1	7	1.7	48	5	15%	7	0.6	51	3	13%
Giant Planet 2	7	1.3	37	2	19%	6	1.0	42	3	14%
Giant Planet 3	0.8	0.9	4	1	20%	0.8	0.5	4	1.2	20%

RESULTS

Binary impostors in central region, LLN:

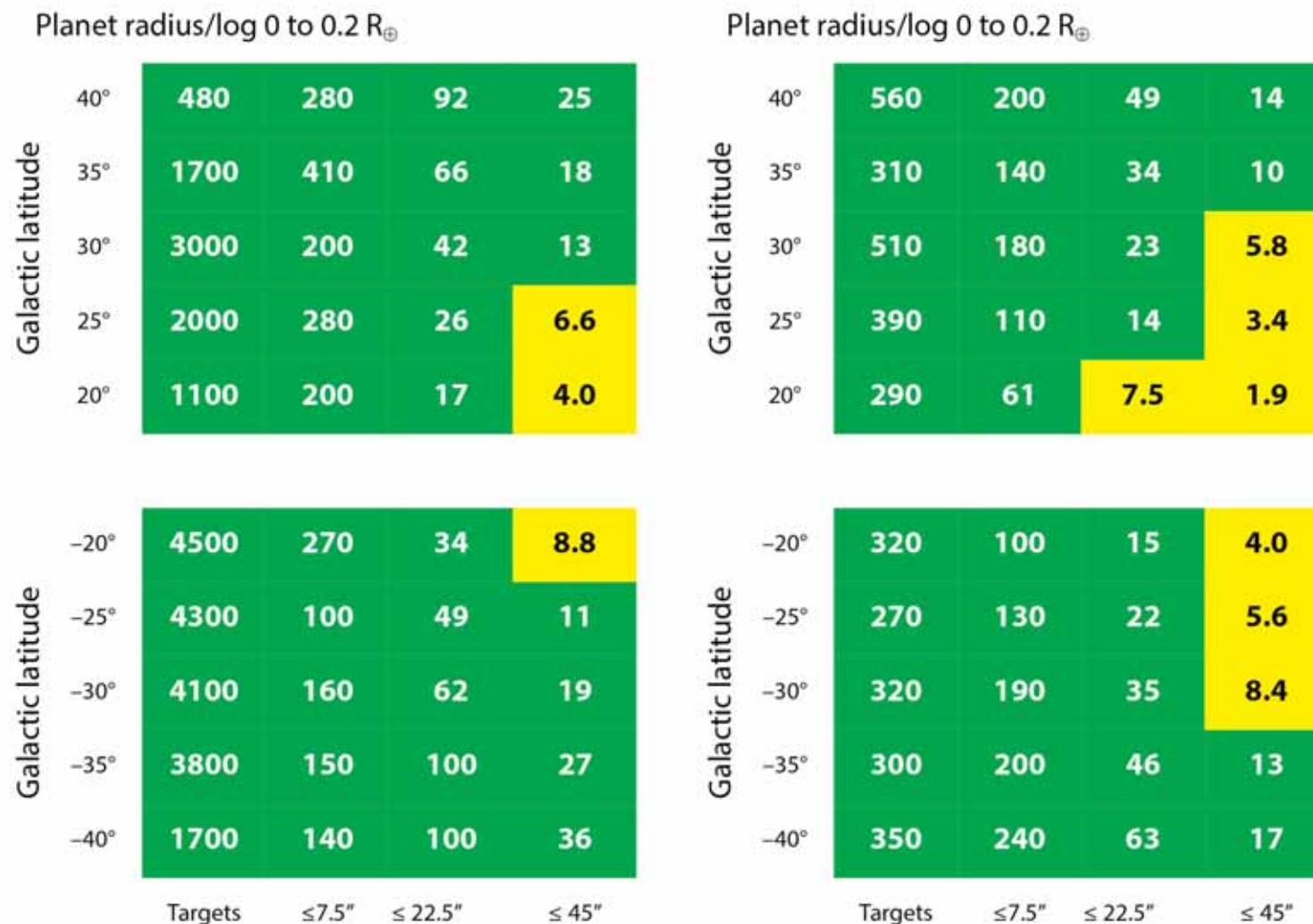
Number of binaries that would mimic a planet:

Planet Size Class	Full field		Central region		Ratio centre/full	
	7.5"	45"	7.5"	45"	7.5"	45"
<i>Mars</i>	0.3	10	0.2	1.5	67%	15%
<i>Earth 1</i>	5	139	1.4	23	28%	17%
<i>Earth 2</i>	37	929	4	116	11%	12%
<i>Small Neptune 1</i>	108	2695	14	231	13%	9%
<i>Small Neptune 2</i>	104	3466	8	204	8%	6%
<i>Large Neptune</i>	94	2832	9	167	10%	6%
<i>Giant Planet 1</i>	90	1932	9	116	10%	6%
<i>Giant Planet 2</i>	96	1223	12	83	13%	7%
<i>Giant Planet 3</i>	119	765	19	75	16%	10%

Error: square root of N

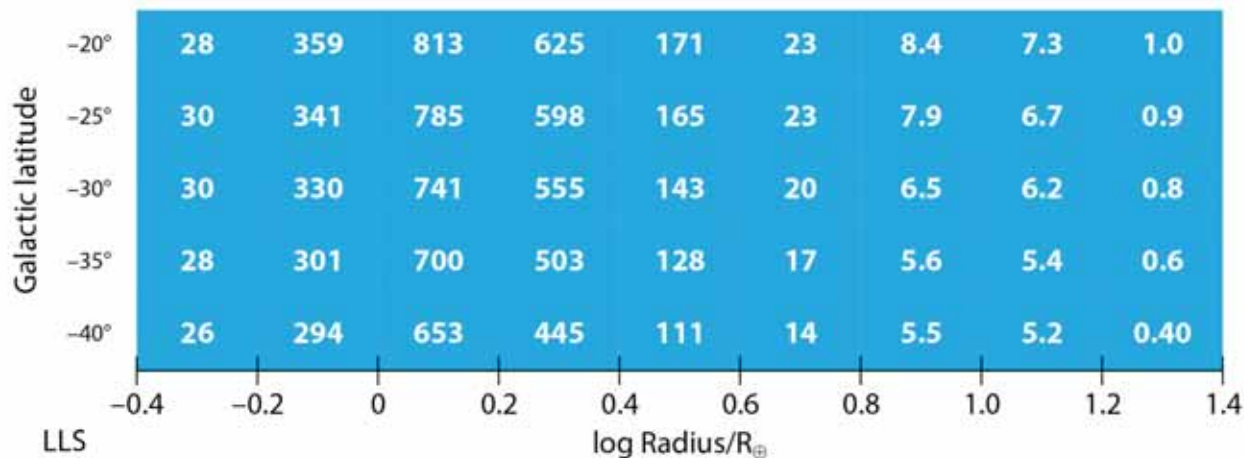
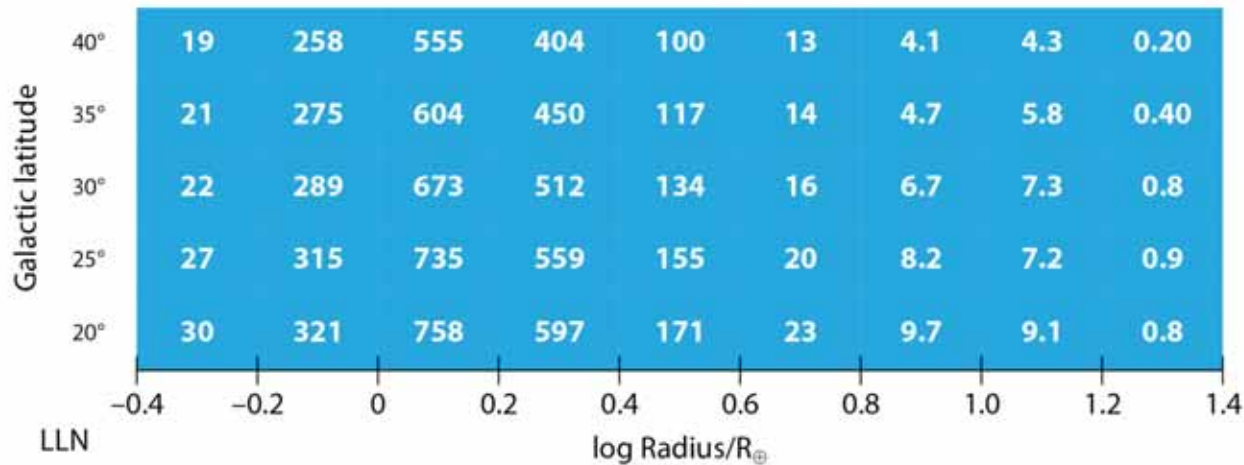
RESULTS

Ratio planets:binaries, central zone only, P5



RESULTS

Number of planets, central zone only, P5



RESULTS



Provisional conclusions

- There is a larger fraction of planets in the region covered by four cameras than for background binaries.
- The proposed LLS field has a higher proportion of terrestrial planets to binaries, as well as a higher number of terrestrial planets, than equivalent latitudes in the LLN field ...

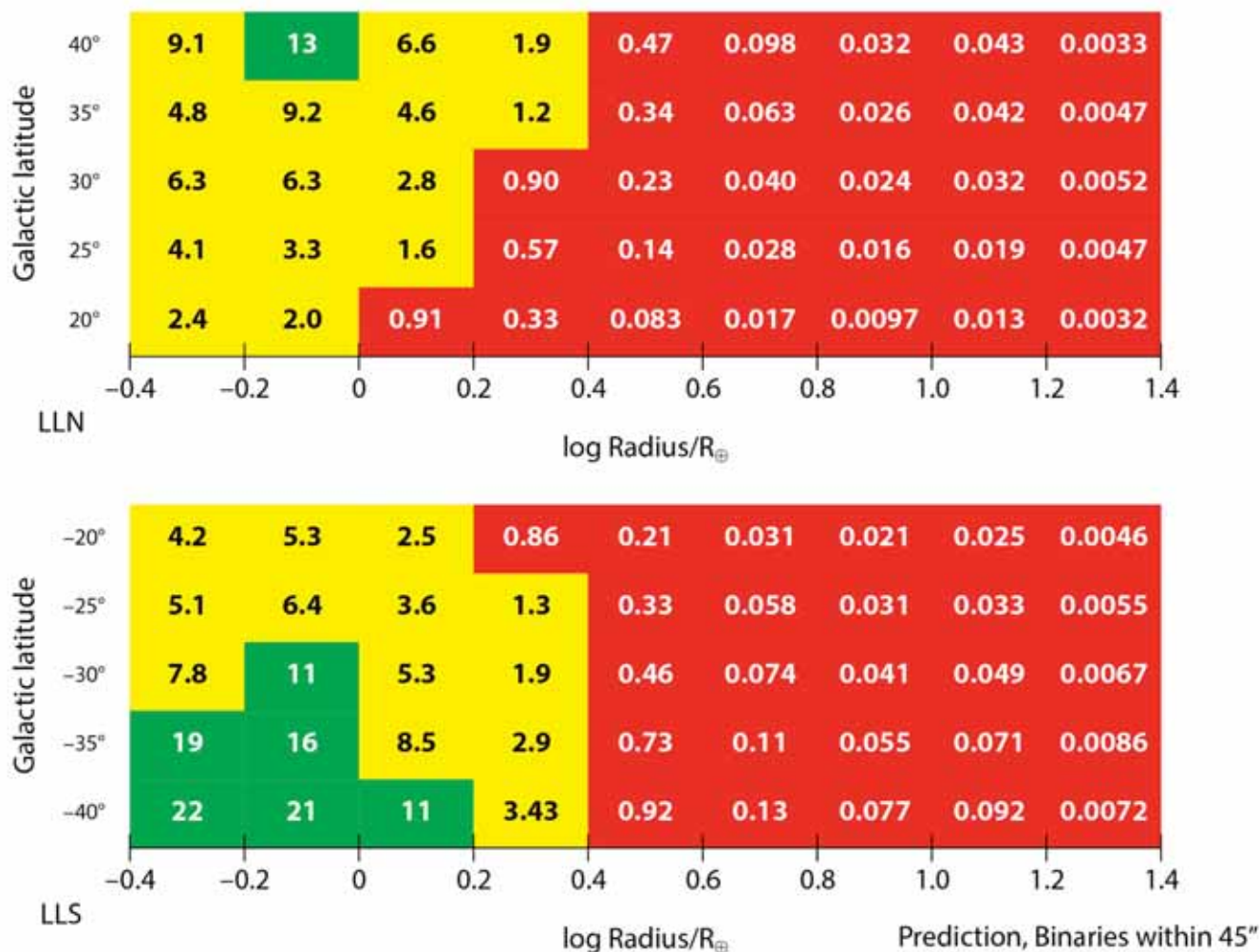
Why?

Blended binaries can be observed up to 10 kpc away:
terrestrial planets can be observed up to 0.3 kpc away.

LLS looks through the Galactic plane,
but is further from the Galactic centre than LLN:
so contains more nearby stars but fewer stars in the deep field
and hence fewer stars in total
in our simulations.

RESULTS

Prediction, P5, ratio planets:binaries,
within same imajette



RESULTS



Next Steps

- Extend the full field deeper to verify the conclusions from the central field.
- Check the calibration of the synthetic fields with Gaia DR2, when available, to verify the conclusion that more terrestrial planets can be observed in the Southern hemisphere than the Northern hemisphere.
- Explore planetary population in multiple systems.
- Explore the role of higher order stellar multiplicity.
- Explore other fields of interest to the PLATO Input Catalogue.



SUMMARY

Kepler data, combined with a synthetic Galaxy, can provide valuable insights into the intrinsic distribution of both planets and binaries in exoplanet surveys.

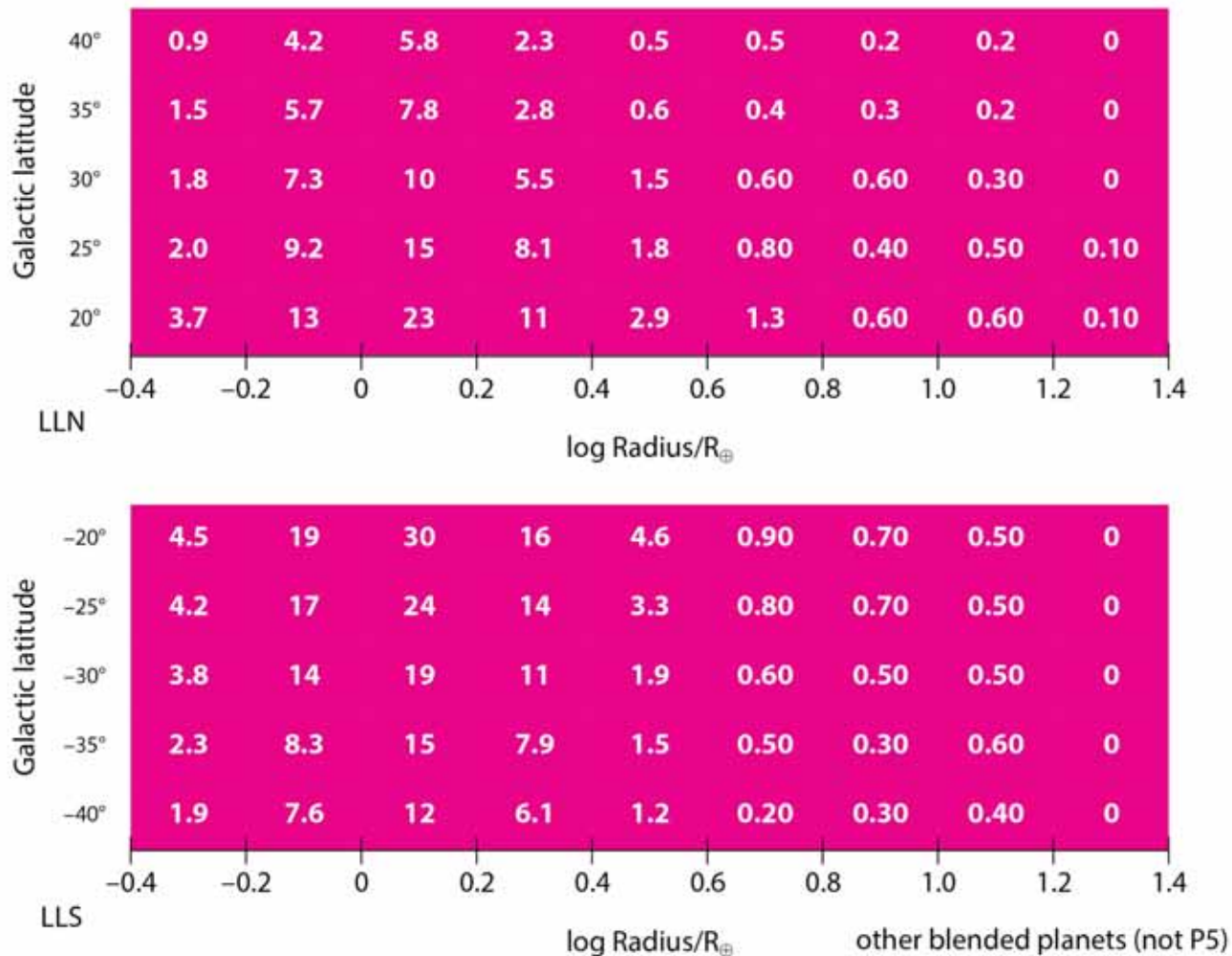
Evidence to date indicates that, for observations of terrestrial planets, it would be safe to shift the centre of the field a few degrees closer to the Galactic plane.

Long Look South appears less contaminated than Long Look North.

Further verification is required.

RESULTS

Non-P5 blended planets, central zone only



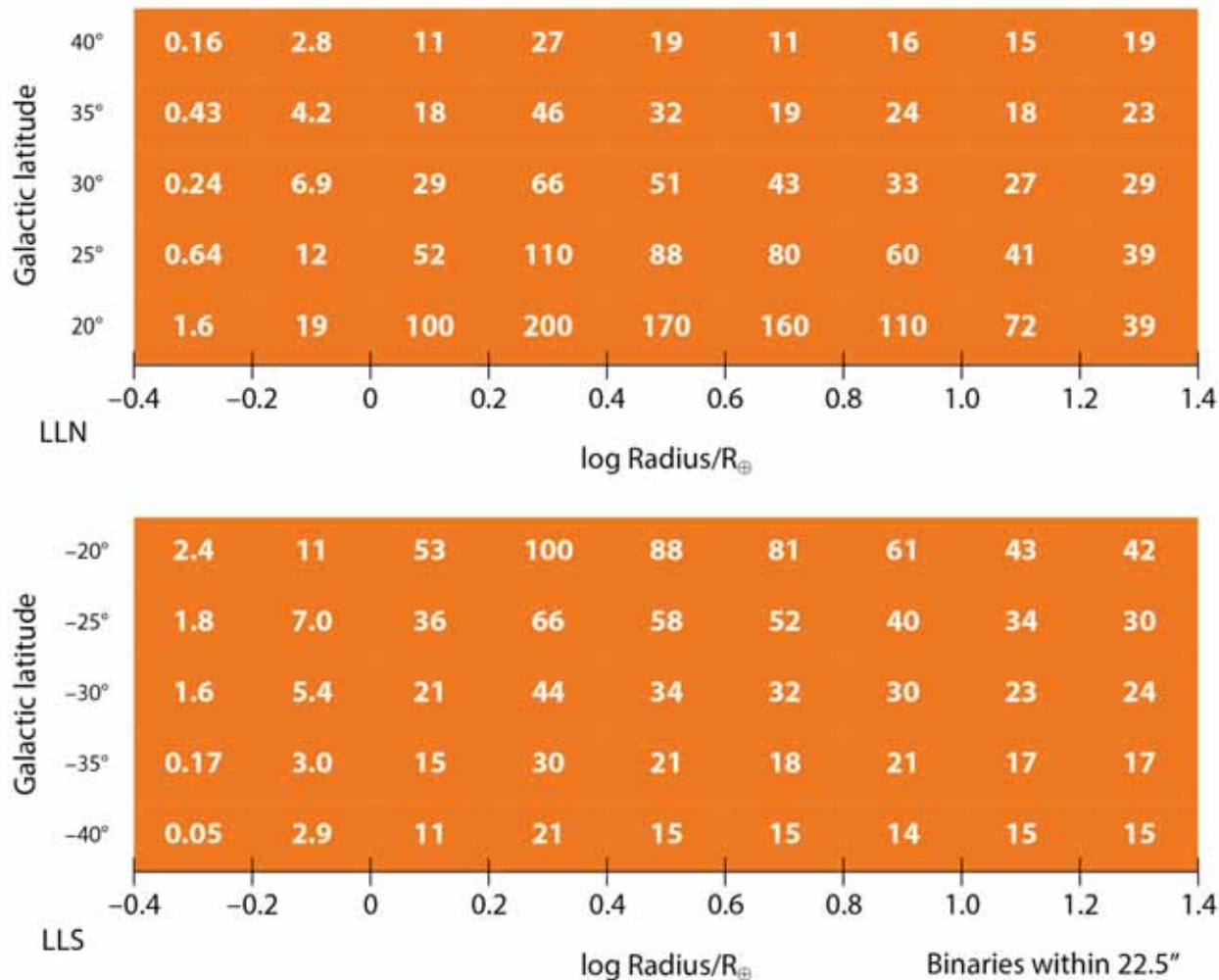
RESULTS

Number of binaries $< 7.5''$, central zone only



RESULTS

Number of binaries $< 22.5''$, central zone only



RESULTS

Number of binaries < 45", central zone only

